APPARATUS AND METHOD FOR MEASURING VISION DEFECTS OF A HUMAN EYE

Cross-Reference to Related Applications

This application is a divisional of application Ser. No. 09/919,374, filed July 31, 2001, now U.S. Pat. No. 6,598,975, which itself is a continuation-in-part of application Ser. No. 09/665,748, filed September 20, 2000, now U.S. Pat. No. 6,270,221, which is a continuation of application Ser. No. 09/274,672, filed March 24, 1999, now abandoned, which claimed priority to Provisional Application having Ser. No. 60/097,086, filed on August 19, 1998 for "Apparatus and Method for Measuring Vision Defects of a Human Eye," commonly owned with the instant application.

Background of Invention

Fi ld of Invention

The invention relates generally to optical aberration measurement and correction, and in particular to projection techniques in the objective measurement and correction of the human eye using a wavefront sensor.

D cription of Background Art

There has been and continues to be a need to provide a person with improved visual acuity. Remodeling of the cornea using refractive laser surgery or intracorneal implants, adding synthetic lenses using intraocular lens implants or precision ground contact lenses or eye glasses provide known solutions. Further, it is known to correct vision astigmatically by surgical modification of myopic or hyperopic astigmatism through laser keratoplasty, keratomileusis, or photorefractive keratectomy. Laser sources are used to erode or ablate surfaces of the eye, typically reshaping the cornea. Prior to and during such surgery, precise measurements must be made to determine required surgical corrections.

The imprecise measurement technique of placing lenses of known refractive power anterior to the cornea and asking a patient which lens or lens combination provides the clearest vision has been improved with the use of autorefractometers, as described in U.S.

Patent No. 5,258,791 to Penny et al., or with the use of wavefront sensors as described by Liang et al. in "Objective Measurement of Wave Aberrations of the Human Eye with the Use of a Hartmann-Shack Wave-Front Sensor," Journal of the Optical Society of America, Vol. 1, No. 7, July 1994, pp. 1949-1957, by way of example. Penny '791 discloses the use of autorefractometer measurements for determining the appropriate corneal surface reshaping to provide emmetropia, a condition of a normal eye when parallel rays are focused exactly on the retina and vision is optimum. Spatially resolved refraction data, in combination with measured existing surface contour of the anterior surface of the eye, enable a calculation of a detailed spatially resolved new contour that provides corrected vision.

It would be an improvement in the art if such vision correction could be made without the need for these contour data, and further without the need for feedback from the patient regarding an appropriate lens. Liang et al. disclose the use of a Hartmann-Shack wavefront sensor to measure ocular aberrations by measuring the wavefront emerging from the eye by retinal reflection of a focused laser light spot on the retina's fovea. A parallel beam of laser light passes through beam splitters and a lens pair that brings the beam to a focus point on the retina by the optics of the eye. Possible myopia or hyperopia of the tested eye is corrected by movement of a lens within the lens pair. The focused light on the fovea is then assumed to be diffusely reflected and acts as a point source located on the retina. The reflected light passes through the eye and forms a distorted wavefront in front of the eye that results from the ocular aberrations. The aberrated wavefront is then directed to the wavefront sensor.

A point source of radiation on the retina would be ideal for such measurements. However, when the perfect eye receives a collimated beam of light, the best possible image on the retina is a diffraction-limited spot. As illustrated by way of example, with Penny et al. and Liang et al., discussed above, and typical for those of skill in the art, collimated parallel beams are used with the optics of the eye being measured to achieve this diffraction-limited spot for such objective measurements. To do so requires that a setup for each patient include a corrective lens or lens combination and adjustments thereto for accommodating that patient's specific visual acuity. Providing a corrective or

lens combination, as well as setting up for its use, becomes cumbersome and time consuming, and requires additional expense. Eliminating the need for such corrective optics is desirable and eliminates a variable within optical measurement systems that typically include many variables. Further, there is a need for providing optical characteristics of an eye without requiring feedback from the patient. By way of example, the patient may be a wild or domestic animal, living or dead.

Summary of Invention

In view of the foregoing background, it is therefore an object of the present invention to provide a refraction measurement system that easily accommodates the measurement of vision characteristics of the eye, even in the presence of finite refractive errors.

It is another object to improve upon the time required for a patient to be in a fixed position during examination, while at the same time providing a useful source of light on the retina of the eye to be measured regardless of the characteristics of the eye of that patient or other patients to be examined.

It is a further object to measure such characteristics without requiring patient or operator feedback.

These and other objects, advantages and features of the present invention, are provided by a method aspect of the invention for measuring optical characteristics of an optical system including the focusing of an optical beam proximate an anterior surface of the optical system, for placing a finite source of secondary radiation on a focal surface of the optical system, which secondary radiation is emitted from the focal surface as a reflected wavefront of radiation that passes through the optical system, transmitting the diffusely reflected wavefront onto a wavefront analyzer, and measuring characteristics of the optical system associated with the reflected wavefront.

In a preferred embodiment, the method includes the step of measuring defects of the eye, which includes the steps of focusing an optical beam onto an anterior surface of the eye, other than the retina, for providing a finite source of secondary radiation on the retina of the eye, which secondary source of radiation is emitted from the retina as a reflected wavefront of radiation that passes through the eye, directing the reflected

wavefront onto a wavefront analyzer, and measuring distortions associated with the reflected wavefront. A preferred embodiment of the invention includes the step of focusing the projected optical beam on the anterior surface of the cornea. In an alternate embodiment the optical beam is focused behind the retina.

An apparatus for effectively performing such measurements includes means for focusing an optical beam onto an anterior surface of the optical system or eye, other than the retina, for providing a finite secondary source of radiation source on the focal surface, or retina of the eye, which finite secondary radiation source is emitted from the retina as a reflected wavefront of radiation that passes through the eye, means for directing the reflected wavefront onto a wavefront analyzer, and a wavefront analyzer for measuring distortions associated with the reflected wavefront. In one preferred embodiment of the present invention, a laser beam is focused onto the surface of the cornea with a long-focal-length lens, which converges the beam through a small angle for passing through the iris of the eye and providing a finite secondary source of radiation source on the retina of the eye, which finite secondary radiation source is emitted from the retina through the optics of the eye as the wavefront to be measured. In an alternate embodiment the apparatus comprises means for focusing the optical beam behind the retina

Brief Description of Drawings

A preferred embodiment of the invention as well as alternate embodiments are described by way of example with reference to the accompanying drawings.

FIG. 1 is a diagrammatic illustration of an apparatus for measuring visual defects of an eye, according to the present invention.

FIG. 2 is a diagrammatic illustration of an eye being measured by the apparatus of the present invention, with the focus on the cornea.

FIG. 2A is a diagrammatic illustration of an eye being measured by the apparatus of the present invention, with the focus behind the retina.

FIGS. 3A and **3B** are diagrammatic illustrations of an ideal eye with perfect vision and an aberrated eye, respectively.

FIG. 4 is a diagrammatic illustration of an eye being measured with collimated light focused on the retina to a diffraction-limited spot.

FIG. 5 is a partial perspective view of a pinhole imaging plate and detector plane of a wavefront sensor used in a preferred embodiment of the present invention.

Detailed Description of Preferred Embodiments

The present invention will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

A preferred embodiment of a measurement apparatus **10** of the present invention is herein initially described with reference to the schematic diagram of FIG.1. A beam **12** of optical radiation is directed into an eye **14** to be measured, so that a small area or spot **16** is formed as a secondary source of radiation in the foveal region of the retina **18** (FIG. 2). Specifically, the beam **12** is focused through a small angle **13** onto an anterior surface **20** of the eye **14**, other than the retina, and in a preferred embodiment of the present invention, focused on an anterior corneal surface **22** of the cornea **24** for further projection through the iris **26** and lens **28** and onto the retina **18**.

In an alternate embodiment of the invention, a projected beam **12'** of optical radiation is directed into an eye **14'** to be measured, so that a small area or measurable spot **16'** is formed as a secondary radiation source in the foveal region of the retina **18'** (FIG. 2A). Specifically, the beam **12'** is focused through a small angle **13'** at a point behind the eye **14'**, after passing through the iris **26'**, the lens **28'**, and the retina **18'**.

By way of further background, consider an "ideal" eye **14i** with ideal vision, as illustrated with reference to FIG. 3A. The ideal eye **14i**, having the ideal cornea **24i** and ideal lens **28i**, will focus a collimated beam of light, illustrated with arrows **30** to a point **32**, as the secondary radiation source, on the ideal retina **18i**. This point **32** would then be a

point source of light that would be diffusely reflected back through the optics of the ideal eye **14i** as a sequence of plane waves **34**. In actual fact, even an eye having perfect vision, as illustrated by way of example with reference to FIG. 4, will produce a diffraction-limited illuminated area or spot **36** as the secondary radiation source on the retina of the eye, under the best possible circumstances. In a typical eye, as illustrated with reference to FIG. 4, such a spot **36** is even larger, where most of the blurring will be due to finite aberrations found in typical eyes. By way of further example, in an aberrated eye **14a**, from the point source **32** distorted wavefronts **38** result, as illustrated with reference to FIG. 3B. Having to deal with a series of distorted wavefronts **38** resulting from aberrations, and further dealing with a blurring of such distorted wavefronts **38** resulting from diffraction effects and the finite aberrations of the eye, results in a spot **36** source of light rather than a point **32** source, representing one of the challenges in measuring the visual defects or an eye.

It is typical in the art of eye measurement to form a collimated beam and attempt to focus the collimated beam onto the retina, using lenses and lens combinations with the optics of the eye to produce the smallest possible spot **36**, as earlier described with reference to FIG 4. Using lenses and focusing techniques typically takes valuable time and includes multiple attempts to focus a spot on the retina with the use of various lenses and lens combinations to accommodate the unique vision of each patient being measured. With the present invention, and the understanding that most of the blurring results from the curvature of the cornea, the present invention eliminates the need to find lenses or lens combinations to minimize the size of the spot on the retina that is used as the secondary source of radiation.

With reference again to the embodiment described in FIGS. 1 and 2, the optical wavefronts **40** scattered from the retina **18** are transferred by a series of optical elements, which will be described in further detail in the following, to a wavefront sensor **42**, which divides each incident wavefront into a group of "wavelets," referred to herein with numeral **50**, using an opaque plate **44** having a planar array of apertures **46** (FIG. 5). Further, the wavefront sensor **42** records the position **48** at which each wavelet **50** passing through the aperture **46** strikes a detector plane **54** such as a charged-coupled device (CCD), herein

provided as one preferred embodiment, the plane being held a fixed small distance **56** behind the plate **44**. The transverse displacement **58** of each wavelet **50** at the CCD detector plane **54** from a collimated light reference position **60** is then used to calculate a wavefront slope at each position of the apertures **46** within the planar aperture array. Alternate methods exist for using partial derivative data resulting from the measurements of the slope to calculate the wavefront **40**. One acceptable approach is that used by Liang et al. in the aforementioned paper, where the wavefront is closely approximated using Zernike polynomials.

At each position **48**, a spot **62** typically extending beyond the light measurement area of one CCD element **64** is produced. As earlier discussed, blurring and a large diffraction-limited spot make it difficult to make measurements. Thus reducing blurring improves measurement at the detector plane **54**.

With reference again to FIG. 1, in one preferred embodiment of the present invention, the apparatus **10** includes the projected beam **12** of linearly polarized light (S-component) emitted from a diode laser **66** (670 nm, 3 mW, by way of example). The beam of light passes through an electromechanical shutter **68**, which controls the duration of light exposure on the eye **14** of the patient. The exposure of the retina **18** of the eye **14** illustrated with reference again to FIG. 2. It is expected that alternate sources of light, for example, noncoherent and nonpolarized as well as alternate light-transmitting techniques, will be recognized by those skilled in the art without deviating from the teachings of the present invention. As herein described, the use of coherent light from a laser and polarization techniques are currently preferred.

When the shutter **68** is open, the projected beam **12**, collimated light from the diode laser **66**, is directed by a long focal length lens **70** for focusing on the anterior surface **22** of the cornea **24** of the eye **14** (FIG. 2), passing through the pupil **72** and lens **28** of the eye **14**, and onto the retina **18** as the small spot **16**. In an alternate embodiment, lens **70** comprises a zoom lens for varying the focus and moving the focus location as desired. By focusing on the cornea **24**, the measurement is minimally dependent on the curvature of the cornea. However, other locations proximate the corneal surface are acceptable.

While diffraction and various aberrations are present, the present invention avoids the aberration effects from the cornea, which typically dominate. The lens **28** of the eye **14** contributes a relatively small aberration effect when compared with that of the cornea **24**. Further, and with regard to the selection of lens **70**, selecting a lens with a short focal length would provide a large angle **13**, a well-focused point **78** on the surface of the cornea **24**, and fewer aberration effects from the cornea . However, a large angle **13** results in an undesirably larger retinal spot **16**. The small angle **13** herein described provides a larger focus point **78** on the cornea **24** but the more desirable smaller spot **16** on the retina **18**. The spot **16** will depend on the wavelength, starting point size, and focal length of the lens **70** selected. In preferred embodiments of the present invention, lenses of approximate one-half meter are selected for the lens **70**. A 100-mm lens **70** has also been effectively used.

In one preferred embodiment herein described, a mirror **74** and polarization beamsplitter **76** direct the beam **12** to a focus **78** on the anterior surface **20** of the cornea **24**. The beam **12**, focused on the anterior surface **22** of the cornea **24**, provides the spot **16** as a light source (about 1.5 milliradians in visual space, by way of example) on the retina **18** of the eye **14** being measured (FIG. 2). Such a spot **16** provides an acceptable substitute for a diffraction limited spot typically sought. By way of one preferred example of use, a method for measuring vision characteristics of the eye **14** includes directing the beam **12** through the long-focal-length lens **70** for providing the small angle **13** (FIG. 2), about an optical path for passing the beam **12** through the pupil **72** of the eye **14**. The beam **12** is first focused at a fixed location **78**, without the eye or patient in place. All measuring equipment, the apparatus **10**, is arranged without the patient in place and at a convenient time prior to measuring. Then the patient is positioned such that the anterior surface of the eye **14** of a patient is located at the fixed location **78**, which in a preferred embodiment is the anterior surface of the cornea. This forms a finite source of secondary radiation, the spot **16**, as herein described, on the retina **18** of the eye **14**, which provides light emitted from the retina **18** and through the pupil **72** as a reflected wavefront,

the wavefront **38** (FIG. 3B). This wavefront **38** is directed onto the wavefront analyzer **42** for measurement.

In a preferred embodiment, the laser power reaching the eye is physically limited to a maximum of 7 μW. In measurements on a human eye using the apparatus **10**, a laser pulse duration of 700 ms was used so that the total energy entering the eye would not exceed 4.9 μJ. For comparison, according to the ANSI standard for direct "intrabeam" viewing, the maximum permissible exposure to a laser at the wavelength used is 530 μJ. Thus the probing laser energies effectively used in the present invention are two orders of magnitude below an "eye-safe" limit.

With reference again to FIG. 1, the light emitted by secondary source of radiation **16** produces the wavefront **40**, a distorted wavefront at the pupil plane due to the eye's aberrations. Diffuse reflection makes the returning light from the retina depolarized, containing not only an S-component but also a P-component polarized light. The polarization beamsplitter **76** in front of the eye **14** will only let the P-component pass through it and downstream of the wavefront sensor **42**. The S-component is essentially totally reflected toward the diode laser **66**. Because the light reflected by corneal surface preserves the polarization of the incoming beam (S-polarized), the corneal reflection is reflected by the beamsplitter **76** and is thus rejected from the path **80** heading toward the wavefront sensor **42**. The P-component of the aberrated wavefront **40** at the subject's pupil plane is then re-created by the combination of lens **82** and lens **84**, at a trial lens plane **86** (FIG. 1). In one preferred embodiment, the diameter and the effective focal length of the two substantially identical lenses **82** and **84** are 40 and 120 mm, respectively. The combination of lenses **82** and **84** forms an afocal image system with the eye's pupil **72** (the object plane) at the focal plane of the lens **82**, and the image plane, trial lens **86**, at the focal plane of the lens **84**. Similarly, lenses **88** and **90** also form an afocal image system with the possible trial lens **86** at the front focal plane of the lens **88** and the lens combination at the image plane at the back focal plane of the lens **90**. The focal plane of the lens **90** is located at the plate **44** of the wavefront sensor **42**, earlier described with reference to FIG. 5. In a preferred embodiment, lens **88** has an effective focal length of

80 mm. Lens **90** has an effective focal length of 120 mm. With the apparatus **10**, measured wavefront slopes leaving the eye **14** are re-created at the aperture plane **44** and magnified by a factor of 1.5. Magnification of the diameter of the wavefront **40** at the detector plane **54** reduces the wavefront slopes by the same degree. This extends the dynamic range of eye aberrations over which the device can measure.

By way of further explanation about the trial lens location or plane **86**, because the wavefront **40** leaving the eye **14** is re-created at this location **86** with unity magnification, a trial lens of known refractive power inserted at this point should exactly compensate for a prescribed refractive error. For example, a perfect five-diopter lens placed at this location should remove five diopters of spherical curvature from an incident wavefront, without altering other aberrations that may exist in the wavefront. The capability of inserting trial lenses at this location **86** extends the dynamic measurement range of the apparatus **10**, without affecting wavefront analyzing capability.

In a preferred embodiment, and with reference again to FIG. 5, the aperture array **46** of the wavefront sensor **42** samples the incident wavefront **40**, which forms focus spots **62** on the detector plane **54**. This is repeated at the detector plane **54** for each aperture within the array **46**. As a result, a localized direction of the wavefront **40** is determined for each of a plurality of wavelets **50** within the array. By way of example, the use of lenslets **92** (as an alternate embodiment of apertures **46** alone), with a focal length of 87 mm and a dimension of 0.768 mm, forms an aerial image of the retinal light source (the spot **16** described earlier with reference to FIG. 2) on the detector plane **54**. If a plane wave, corresponding to an aberration-free eye, were measured, the lenslet **92** array would produce a regular array of focused spots on the image sensor. When the real eye **14** is measured, the wave aberration in the eye will displace the focus spot **62** (FIG. 5), of each lenslet **92** from the reference position **60** to the measured position **50** in proportion to the local slopes of the wavefront **40**. The wavefront sensor **42** measures the local wavefront slopes at an array of sampling locations across the pupil **72**, from which the wavefront **40** itself can be reconstructed.

As illustrated again with reference to FIG. 1, in an alternate embodiment of the present inventive methods, a fixation target **94** may be used to ensure that the patient is looking along the optical axis of the apparatus **10**. The patient is asked to fixate on the target **94** located at the focal plane of a lens **96**. By linearly moving the optics combination **96** of the fixation target **94**, it is possible to provide the eye's spherical correction, and hence to make the fixation target **94** clearly visible to the subject. In one preferred use, the image of the fixation target **94** is intentionally undercorrected for each patient to ensure that the measured eye **14** is focused at infinity. By way of example, the fixation target consists of a dark cross-hair and a number of concentric circles on a white background that is back-illuminated by a tungsten lamp. The patient is asked to look at the center of the cross-hair. The position of the eye **14** in reference to the optical axis is recorded by CCD camera **98**. This CCD camera **98** is conjugate, in effect coupled, to the eye's pupil **72** through a second lens combination **100**, preferably mounted on the camera, and the lenses **82**,**84**. In one method of te present invention, the camera **98** is used to view the eye **14** for aligning the eye within the path of te beam **12** for assuring that the beam passes through the pupil **72**. The camera **98** is also useful in an alternate embodiment of the present invention, for viewing the size of the spot **16** formed on the retina **18** as the user changes the focus point **78** through various anterior surface locations in obtaining an optimum size of the spot **16**.

By way of further example of effective uses of the present invention, the earlier described Zernike coefficients of an eye, taken collectively, can be used as discriminating as fingerprints or DNA. The Zernike coefficients for a person might be used for identification of that person for permitting access to a confidential area, allowing funds to be distributed through an ATM, and the like. Further, the present invention allows eye measurements for a passive subject, such as in the examination of a corpse or sedated animal. The present invention is operable with human eyes, as herein described, as well as those of an animal, bird, or fish eyes, and in particular, nonbiological focusing optical systems such as those found in cameras. The present invention is useful in developing optimized aspheric systems, where an aspheric element need to be designed last by observing and producing a single custom aspheric element that corrects the system. By way of example, the aspheric system may be designed on paper except for the correcting

element, which would be developed experimentally using the present invention as herein described. The design of afocal systems such as a telescope, a searchlight, or a projector which require an added corrective focus element will benefit from the present invention.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and alternate embodiments are intended to be included within the scope of the appended claims.